A THERMAL CONDUCTIVITY EXPERIMENTAL METHOD BASED ON THE PELTIER EFFECT¹

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ABSTRACT

The objective of this work was to test a novel experimental technique to determine

thermal conductivity of low-thermal conductivity materials and tropical foods. The

experimental method was based on the Peltier effect and its application: The

thermoelectric heat pump. This device became practical recently with the development of

semiconductor thermocouple materials. The module assembly used in this work had 127

couples connected in series electrically and in parallel thermally. The heat transfer area of

the module is 3.96 cm x 3.96 cm. The equipment was calibrated using standard materials

of known thermal conductivity: Plexiglas and Bakelite. Then the k values were easily

computed from a energy balance steady-state equation. The results obtained were

summarized on a complete result Table.

KEY WORDS:

Food properties; Peltier effect; steady-state heat transfer; thermal

conductivity; thermoelectric heat pump; tropical foods.

1. INTRODUCTION

Heating and cooling of products processes are frequently used in many processing plants. In all of these heat transfer processes, it is necessary to predict the thermal behavior of the system under study, namely, the temperature distribution and the heat flux. These variables are a function of the nature of the solid, and consequently a function of certain physical properties. Prior knowledge of thermal conductivity (k) is necessary in the design of heat transfer equipment and cooling or freezing process. There are several methods that allow the determination of k. Most of these methods are based on the integral form of the Fourier's law of heat conduction, when they are applied to steady state heat transfer processes. Fourier's law can be described by the following equation:

$$Q = k A \frac{\Delta T}{\Delta x}$$

(1)

where: Q: heat transfer rate, A: heat transfer area, k: thermal conductivity of the sample,

 $\Delta T/\Delta x$: temperature gradient through the sample.

Equation (1) allows a direct experimental determination of the value of k, under steady state conditions. This equation also requires to measure the temperature difference between two points in the direction of the heat flux. In addition, it is required that the heat flux be unidirectional. In previous works, authors [1, 2, 3] have been reported thermal conductivity values for different solids (polymers, tropical fruits and vegetables) and composed materials, under steady and transient conditions. The objective of this work was to test a novel experimental technique to determine thermal conductivity of any material. The experimental method is based on the Peltier effect and its application: The thermoelectric heat pump. This device is employed to heat or cool the piece under study, being possible to calculate precisely the heat introduced to the system. Once the heat transferred and the temperature difference through the solid are known at steady state condition, the thermal conductivity (k) can be calculated using Eq. (1).

1.1 The Thermoelectric Heat Pump

Thermoelectric heat pumps perform the same cooling functions as freon-based vapor compression or absorption refrigerators. In all such units, thermal energy is extracted from a region, thereby reducing its temperature and, then rejected to a heat-sink region of higher temperature. Vapor-cycle devices have moving parts and require a working fluid, while thermoelectric elements are totally solid-state. Four basic physical phenomena can be associated with the operation of thermoelectric devices [4]: The Seebeck effect, the Thomson effect, the Joule effect, and the Peltier effect. The Seebeck effect is the f.e.m. generated when two sides of a thermoelectric module are maintained at different temperatures. The Thomson effect is a heating or cooling effect in an homogeneous conductor observed when an electrical current is passed in the direction of a temperature gradient. The Joule effect is the heating effect observed in a conductor as an electrical current is passed through the conductor. The Peltier effect is the heating or cooling effect observed when an electrical current is passed through two dissimilar junctions. Three of these effects: Peltier, Thomson and Seebeck are reversible phenomena.

Solid state heat pumps have been known since the discovery of the Peltier effect in 1834.

When an electric current flows from one conducting material to another through a junction as shown in Figure 1 [5], energy is brought by the charge carriers to the junction from material A at the left at a rate Q_A , and energy is carried from the junction to material B at the right at a rate Q_B . Because of the energy level of the charge carriers will in general be different in the two materials, Q_A will be greater or less than Q_B . To maintains a constant junction temperature, heat must be transferred (Q_j) to or from the surroundings as shown. The energy level and thus the amount of energy transported is a function of each material. The Peltier coefficient is defined as $\pi = Q/I$ (where Q: heat flow, I: current density).

The junction itself must have a finite electrical resistance so that current flow through it will result in the dissipation of the usual power equal to I^2R (Joule effect, where R: electrical resistivity). This process, of course, is not reversible, but is always a conversion from electrical energy to heat.

The application of this cooling effect remained minimal until the development of semiconductors materials. With the advent of semiconductors materials came the capability for a wide variety of practical thermoelectric refrigeration applications. Thermoelectric refrigeration is achieved when a direct current is passed through one or more pairs of n- and p-type semiconductor materials (Figure 2). In the cooling mode [6], direct current passes from the n- to the p-type semiconductor material. The temperature T_C of the interconnecting conductor decreases and heat is absorbed from the environment. This heat is absorption from the environment (cooling) occurs when electrons pass from a low energy level in the p-type material through the interconnecting conductor to a higher energy level in the n-type material. The absorbed heat is transferred through the semiconductors materials by electron transport to the other end of the junction T_H and liberated as the electrons return to a lower energy level in the p-type material (Peltier effect).

When a temperature differential is established between the hot and cold ends of the semiconductor material, a voltage is generated (Seebeck effect). This voltage is called the Seebeck voltage, and it is directly proportional to the temperature differential ($\alpha\Delta T$). The constant of proportionality (α) is referred to as the Seebeck coefficient.

Ideally, the amount of heat absorbed at the cold end and the heat dissipated at the hot end are dependent on the product of the Peltier coefficient and the current flowing through the semiconductor material. Practically the net amount of heat absorbed at the cold end due to the Peltier effect is reduced by two sources, conducted heat and Joule heat. Due to the differential between the cold and hot ends of the semiconductor material, heat will be conducted through the semiconductor material from the hot to the cold end. As the

current is increased, the temperature differential, and thus the conducted heat, increases because the Peltier cooling effect increases. However, the other loss, Joule heat, is proportional to the square of the current and, therefore, eventually becomes the dominant factor. At any given current, thermal equilibrium is established at the cold end when the Peltier effect at the cold end is equal to the sum of the conducted heat plus one-half of the Joule heat. The other half of the Joule heat goes to the hot end. The net heat dissipated at the hot end is the sum of the net heat absorbed at the cold end plus the applied electric power.

More than one pair of semiconductors are usually assembled together to form a thermoelectric module. A single-stage module as shown in Figure 3a consists of several thermocouples connected thermally in parallel and electrically in series to increase the operating voltage of the module. These thermocouples are interconnected with good electric conductors such as copper. The conductors must be electrically isolated from the device being cooled; otherwise the module will be electrically short-circuited to the surface being cooled. However, the electrical isolation material must also be a thermally conductive material to minimize the temperature difference between the conductor and the device being cooled. The module shown in Figure 3b has a ceramic plate on the top and bottom surfaces of the module. Alumina ceramics typically provide the electrical isolation and thermal conductance that satisfies this requirement.

In the operation of thermoelectric modules it is reasonable to assume that the heat flows only in the x direction, this means that there is no heat flow except through the junctions [4]. Moreover, all the heat may be considered to flow through the plates which sandwich the thermoelectric couples. To find a formula for Q_C or Q_H it is necessary to look at one of these thermoelectric couples. As shown in Figure 3b the direction of the current is opposite for n- versus p- material. Most of the properties of these two materials differ from each other, in fact. If one makes use of these differences, it is possible to derive the equation of the heat flow for a couple having the equation of heat flow through a bar.

Under steady-state conditions, the differential equation for energy flow through a unit volume is written as:

$$TI\frac{\partial \alpha}{\partial x} + \tau I\frac{\partial T}{\partial x} - \rho I^2 - \frac{\partial}{\partial x} \left(\kappa \frac{\partial T}{\partial x}\right) = 0$$
 (2)

where: T: temperature, x: coordinate, I: current density, κ : thermal conductivity of the material, α : Seebeck coefficient, τ : Thomson coefficient, ρ : electrical resistivity.

To solve Equation (2), a numerical method would be applied knowing the transport properties as a function of location temperature. Therefore, it is rather necessary and convenient to assume averaged transport properties. Equation (2) will be applied for the n- and p- arm, but with different properties and an opposite direction of current. Thus, adding Peltier terms, one can have the equation of heat flow at the junction of two dissimilar conductors [4]:

Heat flow at
$$T_C$$
: $q_C = \alpha T_C I + \frac{1}{2} \overline{\tau} I \Delta T - \frac{1}{2} I^2 \overline{R} - \overline{\kappa} \Delta T$

(3)

$$\mbox{Heat flow at T_H:} \qquad \ \ q_{_H} = \alpha \, T_{_H} \, I - \frac{1}{2} \overset{-}{\tau} I \Delta T + \frac{1}{2} \, I^2 \, \overline{R} - \overset{-}{\kappa} \Delta T \label{eq:qH}$$

(4)

where: $\Delta T = T_H - T_C$,; α : net Seebeck coefficient of a couple at the temperature of the junction. \overline{R} , κ , $\overline{\tau}$: average properties of a couple in the temperature range of $T_C < T < T_H$.

For a module that contains n couples connected electrically in series and thermally in parallel:

$$Q_{C} = n q_{C} = \alpha_{m} T_{C} I - \frac{1}{2} I^{2} R_{m} - \kappa_{m} \Delta T$$

(5)

$$Q_{H} = n q_{H} = \alpha_{m} T_{H} I + \frac{1}{2} I^{2} R_{m} - \kappa_{m} \Delta T$$

(6)

where: $\Delta T = T_H - T_C$; α_m , R_m , κ_m : mean values of the transport properties of the module in the temperature range of $T_C < T < T_H$.

2. EXPERIMENTAL SETUP

The experimental arrangement is shown in Figure 4. Thermoelectric device is a Peltier module MELCOR [7], model CP1.4-127-045L, low current ceramic insulated thermoelectric, contains 127 thermocouple, each element 0.045 in (1.143 mm) in length and 1.4 mm square in cross section. Thermoelectric material is a quaternary alloy of bismuth, tellurium, selenium and antimony with small amounts of suitable dopents, processed to produce an oriented polycrystalline ingot with superior anisotropic thermoelectric properties. Metallized ceramic plates of 1.56 in (3.96 cm) x 1.56 in (3.96 cm), afford maximum electrical insulation and thermal conduction. The operating temperature range is -150 °C to +80 °C. The mean values of the transport properties for this module are reported as function of T [8].

Before the experiences, the thermoelectric module surfaces were cleaned and degreased. Then a thin continuous film of thermal grease was applied to the surfaces of thermoelectric device to minimize contact resistance. The cold surface of the module, was located over the finned heat exchanger. In order to promote the heat transfer a fan was placed beneath the finned heat exchanger.

The sample was sliced and placed on the top of the ceramic plate. To guarantee the one-dimensional heat flow, the sample was isolated all around with a block of a very low conductive material. Three very thin thermocouples (J type) were placed on both sides of the sample and in the cold surface of the thermoelectric module to measure T_H , T_C and T_S (sample external surface temperature). The temperature and intensity of current (supplied during the experiment) were registered in a data acquisition system.

3. RESULTS AND DISCUSSION

To support the proposed method, two samples (Plexiglas and Bakelite) with known thermal properties were selected as test materials. Their thermal conductivity values are reported on Table I. As it can be seen, all the tabulated values are within the ranges reported in the literature. The latter validates the assumptions leading to the proposed mathematical model and the experimental methodology used.

The values of thermal conductivity and water content (wc) for the tropical foods selected in this work — Carrot (*Daucus carota*), Yucca (*Manihot dulcis*) and Sugar beet (*Beta vulgaris*) — are summarized on Table I. The heating process last around seven minutes. This test time is considerable minor than the one required for the Guarded Hot Plate Method [11]; due to the size of the sample is considerable smaller and the heat transfer process (Peltier effect) is more effective than the traditional wired hot plate. When a small sample is required for any thermal method, it is easier to achieve a uniform thickness and temperature. Using cascaded thermoelectric modules (or a device with more thermocouples) it is possible to reduce the whole cooling or heating time of the thermal conductivity test until few seconds. This processing time would be similar to those used in the food industry.

The values of thermal conductivity calculated in this work for sugar beet, yucca and carrot were very similar to the ones reported in the literature [2, 10]. In general, thermal conductivity varies in the range from 0.6 to 0.88 W·m⁻¹·K⁻¹. The deviations between experimental results and reported values in the literature can be attributed to the variations in the water content and the intrinsic chemical and physical differences due to the nature of the roots. For this reason, it is necessary to measure thermal properties for the specific kind of food, mainly due to the enormous variety of them. The proposed experimental method is an excellent way to calculate thermal conductivity easily, accurately and at low cost.

4. CONCLUSIONS

The proposed method to determine solid thermal conductivity based on the Peltier effect (thermoelectric module) shown satisfactory results for all the standard samples used. The last fact indicates that thermoelectric refrigeration is a highly reliable and practical method of cooling or heating small-volume samples with a low cost and high efficiency.

The values of thermal conductivity calculated in this work for sugar beet, yucca and carrot were very similar to those reported in the literature (from 0.6 to $0.88~W\cdot m^{-1}\cdot K^{-1}$). The total test time required is similar to the cooling and heating time used by the food industry in many of its variety processes.

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Table I: Water content (wc) and thermal conductivity of samples studied in this work

Sample	Thickness (mm)	wc (%)	k from this work $(W \cdot m^{-1} \cdot K^{-1})$	k from literature (W·m ⁻¹ ·K ⁻¹)
Bakelite	6.5		1.5 @ 330 K	1.4 @ 300 K [9]
Carrot	6.5	66	0.7 @ 320 K	0.6 @ 80-90% wc [2,10]
Yucca	8.2	61	0.61 @ 320 K	0.63-0.66 @ 57-70% wc [2]
Sugar beet	9.95-10	87	0.77-0.88 @ 320 K	0.63 @ 55-65% wc [2,10]

FIGURE CAPTIONS

Figure 1	Current flow through the junction of two different materials (Peltier effect)		
Figure 2	Thermoelectric heat pump.		
Figure 3	(a) Single-stage thermoelectric module. (b) Thermoelectric couple.		
Figure 4	Experimental arrangement.		











